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INFRARED ABSORPTION HYGROMETER

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ABSTRACT

A recording infrared absorption hygrometer which measures the absolute humidity in a 1-meter light path is described. Record is obtained on a remote self-balancing potentiometer. Use is made of the 1.37μ water vapor absorption band and a 1.24μ reference band. Isolation is by means of transmission type interference band-pass light filters. Infrared detection is by means of a lead sulfide photocell and amplifier. Isolation filters are contained on a sector wheel which is rotated to chop an infrared beam. A self-balancing null system is employed whereby the energy in the absorption band is kept equal to the energy in the reference band at all times. Balance is maintained by automatically varying the temperature of the lamp supplying the infrared energy, and the temperature of the lamp is a measure of the water vapor in the sensing path. An index of the lamp temperature is obtained by means of a monitor photocell, and meter or recorder. Included is a discussion on the calibration and field tests made on the instrument at the Weather Bureau Laboratories, Washington, D. C.

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INTRODUCTION

In a recent paper the National Bureau of Standards lists fifteen distinct methods for measuring atmospheric water vapor [1]. In addition to describing the principles of operation of the hygrometers commonly employed by the meteorologist, the paper gives many references to other instruments, including those which are inherently suitable for use only in the laboratory. In pointing out the de-

ficiencies of the more commonly used schemes for measuring water vapor the publication emphasizes the need for further instrumental development in this field, especially equipment for measuring water vapor at low temperatures. Of those methods now available only the dew point indicator seems to have any promise of meeting requirements; current dew point instruments, however, are complicated in design and operation and have two primary defects as yet not completely eliminated. One is the uncertainty at temperatures below 0° C. as to whether ice or supercooled water forms on the sensing surface. The other is the lack of adequate reliability in any but research instruments in measuring relative humidity or dew point at low temperatures.

The less common hygrometric methods such as the gravimetric, optical, chemical, etc., while of extreme importance in certain specialized work, in general, have been used by the meteorologist only on an experimental basis. The reason for this is that equipment built around these methods has been unacceptable to the meteorologist either because of its complexity or the time involved in making measurements. In general these less common methods can be classed as laboratory equipment unsuited for general meteorological application.

ADVANTAGES OF ABSORPTION SPECTRA METHOD

One of the less common methods, however, because of its inherent advantages bears further consideration. This is the absorption spectra method. Fundamentally this is an optical method based on the absorption effected by water vapor in certain spectral regions. Basically the absorption spectra instrument comprises a beam of energy and some scheme for measuring the attenuation of this beam due to the presence of water vapor. The absorption spectra instrument has several advantages not found in other hygrometers. First, as to the matter of sampling, it is possible to sample instantaneously any desired path length of atmosphere from a few inches to thousands of feet, and in so doing arrive at an integrated value of the absolute humidity in the path in question. If the path is appreciable, the value obtained is more representative than that obtained by spot sampling. Second, the method has an advantage over others because of the nature of the absorption function. Surprisingly enough, the absorption function results in an increase of sensitivity of the measuring equipment as the humidity concentration decreases. In contrast, the psychrometer, hair hygrometer, electrical hygrometer, and even the dew point apparatus all become less sensitive or more difficult to operate as the air temperature falls and the humidity becomes less. Since no change of state is involved in the absorption spectra method the equipment will operate as well below the freezing point as above it. Third, the speed of response is limited only by the speed of the indicator or recorder. This makes the method ideal for use in measuring humidity from an airplane or under any circumstance where rapid changes of humidity can occur. Finally, the method in no way alters the sample concentration by either adding or subtracting water or changing the state of any part of the sample as occurs in the psychrometric or dew point methods.

Because of these outstanding advantages the Weather Bureau has for some time been interested in developing an absorption spectra hygrometer which would be simple and dependable enough for special if not general meteorological service. A paper entitled, "A Spectroscopic Hygrometer" describes earlier work by the Weather Bureau along this line [2]. In this work the instrumental equipment consisted primarily of a transmission grating spectrophotometer and a tungsten lamp projector. Vacuum radiation thermocouples and a high sensitivity galvanometer were employed to measure the spectral energy. Although this system gave good results in making water vapor measurements over paths up to 150 feet, because of the galvanometer equipment it could not be considered satisfactory for field use.

NEW DEVELOPMENTS

This earlier work indicated clearly that if an infrared absorption hygrometer is to be suitable for general service, it must comprise the simplest of optical components and

employ an infrared detector which will operate in conjunction with an a-c amplifier. Recently the possibility of meeting these design requirements has been greatly enhanced through the development of two devices. These devices are the transmission type interference narrow band-pass light filter and the photoconductive lead sulfide cell.

The transmission type narrow band-pass light filter consists of two highly reflecting but partially transmitting films of silver separated by a transparent spacer film deposited on a glass plate and protected by a cover glass. The separation of the silver films determines the wave length position of the pass band. Where the optical separation of the silver films is effectively a half-wave length or a multiple of half-wave lengths apart, there is high transmission, but light of other wave lengths is reflected rather than transmitted. Filters of this type have been available commercially for several years, but it has been only recently that they have become available with pass-bands out in the infrared where the deep water vapor absorption bands are located [3 and 4]. These infrared filters simplify the design of absorption spectra equipment since through their use an entire spectrophotometer can be replaced by an appropriate pair of light filters and a simple collimating system. In using such filters auxiliary filters are required to eliminate undesirable pass bands either of higher or lower order. In first order filters there is no pass band on the long wave length side of the selected band. As a general rule filters for use in the near infrared should be of the first order, in which case there are available glass filters which can be employed to eliminate the higher order pass bands in the visible.

The photoconductive lead sulfide cell was developed in Germany and in the United States during World War II.¹ This cell is sensitive out in the infrared region to about 3.5 microns. Its sensitivity in the area between 1 and 2 microns, where many water vapor bands are located, is many times greater than a good laboratory bolometer. This photoconductive cell because of its extreme sensitivity, fast response (in the order of 200 micro-seconds), and its dark impedance (0.1 to 2.0 megohms), is ideal for use in conjunction with an a-c electronic amplifier [5].

Foreseeing the importance of these two new developments to the design of a practical absorption spectra hygrometer, the Weather Bureau resumed work in this field, initiating a project to develop an instrument suitable for meteorological service. This paper, a preliminary report on this project, describes an infrared absorption hygrometer which employs narrow band-pass light filters and a lead sulfide cell.

¹ Early experimental cells were procured with the aid of the Bureau of Ordnance of the Navy Department. Such cells are now available from various sources in the United States.

THEORETICAL CONSIDERATIONS

To understand some of the design problems involved in the development of an absorption spectra instrument, a brief discussion of the underlying nature of the water vapor absorption function is presented.

It has long been established that there are many regions in the electromagnetic spectrum that are sensitive to water vapor. In particular the water molecule has three deep fundamental bands caused by normal molecular vibrations. These bands are located at 6.26 , 2.74 , and 2.66μ [6] with numerous overtones and combination bands extending into the visible as low as 0.57μ . The four most important of these overtones and combination bands are centered at 0.937 , 1.13 , 1.37 and 1.9μ . In general, as the region of absorption approaches the fundamentals, the absorption becomes progressively greater. On the long wave length side of the 6.26μ fundamental, lines of the rotational band are observed out into the far infrared.

The fundamental technique usually employed in measuring water vapor by the absorption spectra method is due to Fowle [7]. The method consists essentially of isolating the radiation in two regions of the spectrum, one in a water sensitive absorption region and the other close by where no absorption occurs. The ratio of the energy intensities of these two regions can then be used as an index of the amount of water vapor in the radiation path. For example, if the amount of absorbing vapor changes, the energy in the absorption band changes while the energy in the region where no absorption occurs remains unaltered, thus effecting a change in ratio. If, on the other hand, the radiation changes due to the presence of haze, smoke, mist, etc., the energy in both regions changes in the same proportion resulting in no change in ratio. This statement assumes the regions of interest to be situated so close together spectrally that the differential scattering effected by small particles is negligible.

In a spectral region of continuous absorption, the relationship between absorption and the absorbing mass can be expressed as an exponential function. It has been shown, however, that such a function is not valid for water vapor since its absorption spectra are not continuous but rather are regions consisting of numerous closely spaced lines, irregular both as to spacing and intensity [8]. In an absorption band or part of a band, the attenuation due to water vapor is a complicated function of the pressure and temperature of the air and the mass of water per unit volume of the air through which the radiation passes. At a given temperature, the percent absorption can be represented as a function of $(MP)^k$ where M is the water mass and P is the pressure. For relatively low absorptances, the absorptance increases almost linearly with the square root of the water mass in the path. For large absorptances, the increase in absorptance is somewhat less than the square root of the water mass [9]. The fact that the water mass absorptance function is complicated does not detract from the absorption spectra method since an

empirical relationship between absorptance and absorbing mass under different atmospheric conditions can be determined experimentally. Regardless of what the exact theoretical function may prove to be, it is well established that within limits, the rate of change of absorption increases with a decrease of water vapor in the absorption path. This is a fortunate circumstance since this characteristic results in increased sensitivity at low water vapor concentrations such as exist in the atmosphere at low temperatures.

Preliminary work indicated that for best results the maximum absorption should be kept to 40 percent or less and probably much less [2]. This means that in designing a hygrometer some care must be exercised in choosing an absorption band since as has been pointed out, the coefficient of absorption varies from band to band. For water vapor concentrations usually encountered in the atmosphere from winter to summer, the range may be from a few tenths of a gram to about 35 grams per cubic meter. It has been found that the harmonic band centered at 1.37μ gives a maximum absorption of the order of from 10 to 15 percent with short light paths. The instrument described utilizes the 1.37μ region for the absorption band and for comparison uses the area centered at 1.24μ where no water vapor absorption occurs. Light paths of from 1 to 3 meters have been employed, although the instrument described utilizes a 1-meter path in the interest of portability and convenience.

SYSTEM DESCRIPTION

1. SPLIT BEAM

As usually occurs in instrumental developments, the hygrometer underwent considerable modification before reaching its present form. In the earlier stages of development a split-beam sensing light path was employed. Later, it was found more advantageous to use a single-beam path. Since, however, it is somewhat easier to explain the operation of the split-beam path, this scheme will be described first. Figure 1 is a schematic diagram of the split-beam arrangement. A beam of light from a tungsten lamp is brought into collimation by a simple short focus plano-convex lens. This beam is effectively split into two parts by placing two appropriate first order narrow band-pass transmission type interference filters side by side symmetrically in the collimated beam just beyond the collimating lens. The filters employed have their centers of transmission located at 1.37μ and 1.24μ , respectively, each having band-pass half widths of about 50 millimicrons. Since the radiation in the 1.37μ region is sensitive to water vapor, this half of the beam is attenuated by the presence of water vapor in the sensing path, while the part of the beam passing through the 1.24μ filter is insensitive to water vapor. For the sake of brevity, the part of the beam passing through the 1.37μ filter will be referred to as the absorption band beam and the beam passing through the 1.24μ filter, as the reference band beam.

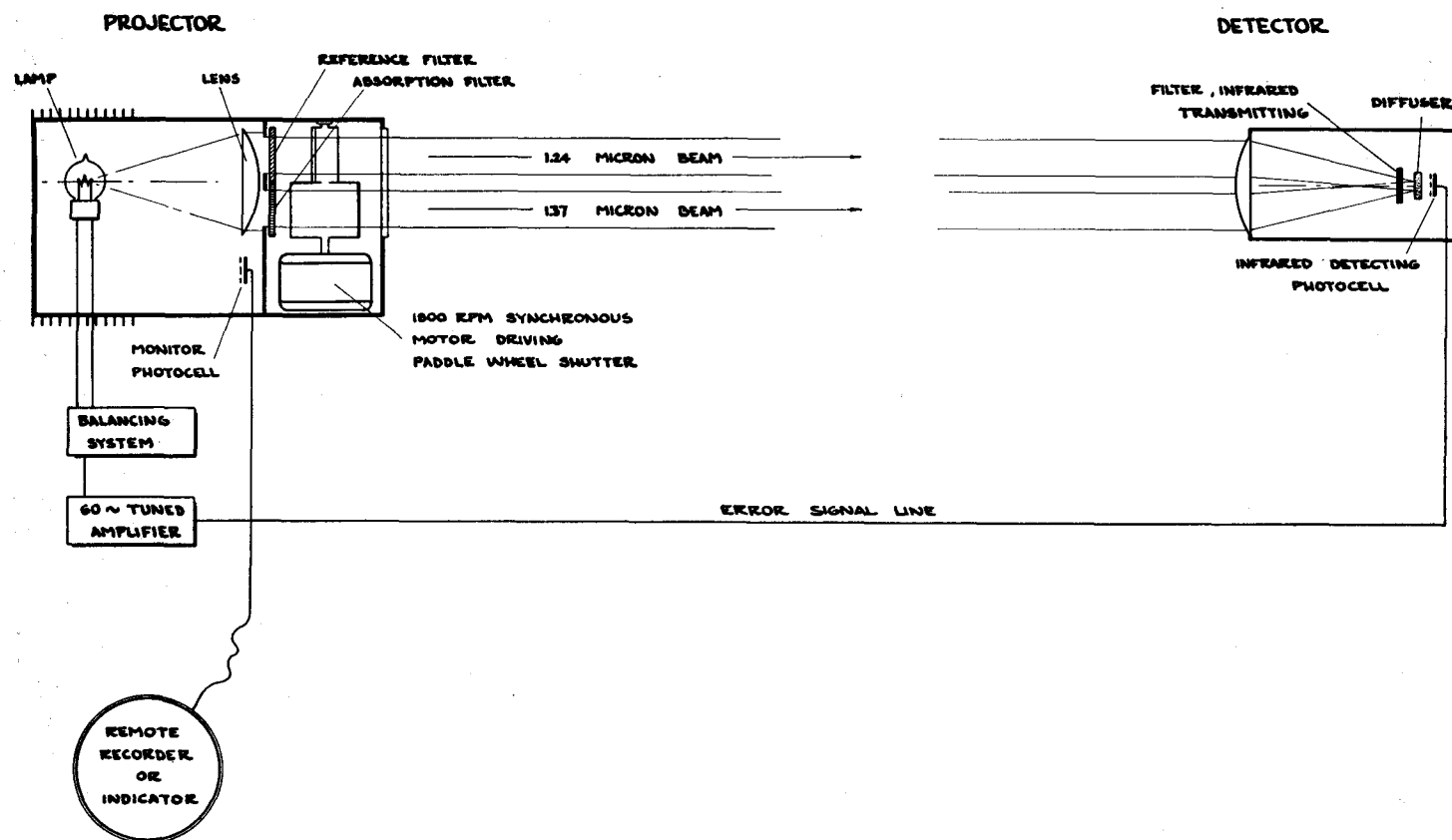


FIGURE 1.—Infrared hygrometer, schematic diagram of the split-beam system.

These two beams are interrupted 60 times a second by means of a mechanical chopper placed just beyond the filters (see fig. 1). The chopper is of the paddle wheel type having two opaque blades oriented 90° to each other. This type of chopper when used in conjunction with appropriate diaphragms will vary the flux of the beams in a sinusoidal manner. Since the chopper blades are 90° apart, one rotating in one beam and the other in the other beam, the two emerging beams are interrupted sinusoidally so that the peak energy from one occurs simultaneously with the zero energy of the other. After passing over the sensing path, the two beams are brought to focus on an opal glass diffusing plate by a plano-convex lens. An infrared transmitting glass filter and lead sulfide cell are located behind the diffusing plate. The diffusing plate serves to disperse the light uniformly over the photocell, thus nullifying the effect of point-to-point variation in photocell sensitivity and spectral character of the image of the lamp filament. The infrared transmitting glass absorbs the energy passed by the second and third order pass bands of the interference filters. Since each beam is alternately interrupted at a frequency of 60 cycles per second the photocell signal as seen by the amplifier consists of two 60-cycle components, each 180 electrical degrees out of phase with respect to the other. When the light flux in each of the two beams is such that the two signal components are equal, the one will cancel the other and no signal will be observed. If, however, one com-

ponent is more intense than the other a signal will result which has a phase depending on which beam is the stronger. When the two components are equal and water vapor is allowed to enter the sensing path, the energy in the absorption band beam will be attenuated while the energy in the reference beam will remain unchanged. As a result a signal will develop at the output of the amplifier, the amplitude of which will be a function of the water vapor in the sensing path.

The magnitude of this signal can be used as an index of the water vapor in the sensing path, and as a first approach to the problem this was tried. It was soon discovered, however, that such a scheme is impractical if measurements are to be made with a reasonable degree of accuracy. The reason for this is that the method depends on the gain of the amplifier, output of the lamp, and sensitivity of the photocell, all of which are subject to change with time, temperature, line voltage, etc. It might be added that these same troublesome variables were responsible for discarding an earlier idea which involved measuring separately the energy in each beam and taking the ratio of these energies as an index of the water vapor in the sensing path.

2. NULL METHOD

In view of the difficulty of stabilizing the amplifier, lamp, and photocell to the degree required, it was decided early in the work that a satisfactory instrument could

only be achieved through the use of a scheme for either measuring the ratio of the beam energies directly or holding the ratio to some fixed value. A null method appeared to be the simpler solution. In the null method employed, the ratio of the beam energies is made equal to unity when a water vapor reading is taken. This means that a reading is taken when the output of the amplifier is zero (null), as the absorption band beam signal is 180° out of phase with the reference band beam signal. It means also that the reading is independent of amplifier gain and photocell sensitivity as long as these factors are maintained above a certain value. Since the method requires a beam energy ratio of unity for reading, regardless of the amount of water vapor in the sensing path, some means has to be provided for changing the energy in either one or both of the beams to compensate for water vapor changes. The means must also provide an index as to the change in beam energy ratio effected by a change in water vapor. A simple scheme that gives a high degree of sensitivity has been developed for doing this.

It can be shown by Planck's Law that for a radiating black body it is possible within limits to change the ratio of energies emitted at two wavelengths by changing the temperature of the body. This phenomena is utilized in the instrument and makes it possible to null the amplifier signal by merely adjusting the temperature of the lamp furnishing the radiation. At the same time the temperature of the lamp is an index of the water vapor. Figure 2 shows the change in ratio of the energy of the absorption band beam to the energy in the reference band beam as the lamp temperature is varied from $2,100^\circ$ to $3,000^\circ$ K. It is apparent that a relationship between the temperature of the lamp for a null signal and the amount of water vapor in the sensing path, if established, would constitute a calibration of the instrument.

It is not practical to measure the temperature of the lamp directly, however, and a dependent quantity must be measured instead. An index of the lamp temperature can be obtained by means of a voltmeter or ammeter in the lamp circuit or by measuring the total radiation or illumination of the lamp directly. The method employed consists of measuring the energy in a portion of the lamp spectrum by means of an improved type temperature-insensitive selenium barrier layer photocell [10]. The monitor photocell is exposed to the light from the lamp but is outside the light beam. (See fig. 1.) The response of the photocell can be read on a microammeter or recorded on a self-balancing potentiometer. This arrangement gives a sensitivity many times greater than is obtained by measuring either the lamp voltage or current.

3. SELF-BALANCING

To eliminate the necessity of manually adjusting the lamp to obtain a null signal an automatic self-balancing system is employed. Servo systems consisting essentially of an amplifier, phase sensitive network, and a small two-

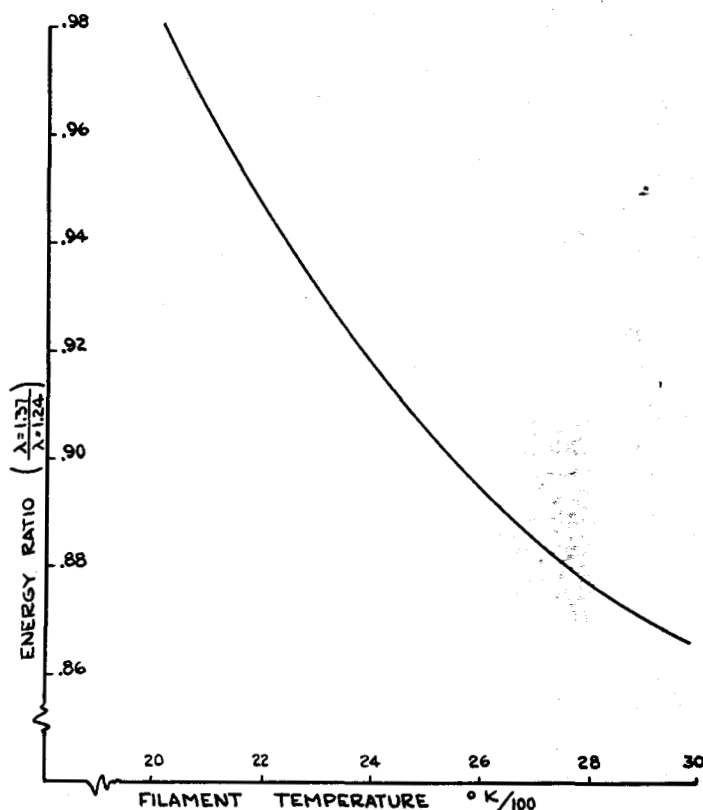


FIGURE 2.—Energy ratio vs. lamp temperature for $\lambda=1.37\mu$ and 1.24μ .

phase reversible motor are employed in many modern instruments. Such systems are so designed that if an appropriately phased 60-cycle signal is fed into the amplifier the motor will turn in one direction. A 180° reversal in the phase of the signal will cause the motor to turn in the opposite direction, and with no signal the motor will remain idle. Equipment of this kind is employed in practically all self-balancing recording potentiometers. A modified form of this equipment is used in the hygrometer to automatically adjust the lamp temperature so that the reference and absorption band photocell signals are balanced to a null at all times. This is accomplished by driving a variable transformer by the servomotor. The design is such that when water vapor enters or leaves the sensing path, upsetting the balance between the reference and absorption band signals, the servomotor turns the variable transformer in such a direction as to change the lamp temperature until a balance is restored. Thus a continuous automatic balance is maintained without the necessity of personal supervision or manual adjustment. The scheme makes possible a recording of the amount of water vapor in the sensing path, since with continuous balance the output of the monitor photocell is a measure of the water vapor at all times.

An additional advantage of the self-balancing system is the high sensitivity which may be obtained through its use. Usually the sensitivity of such equipment is limited by the noise level of the sensing element at the input of the amplifier. It has been found that because of the high

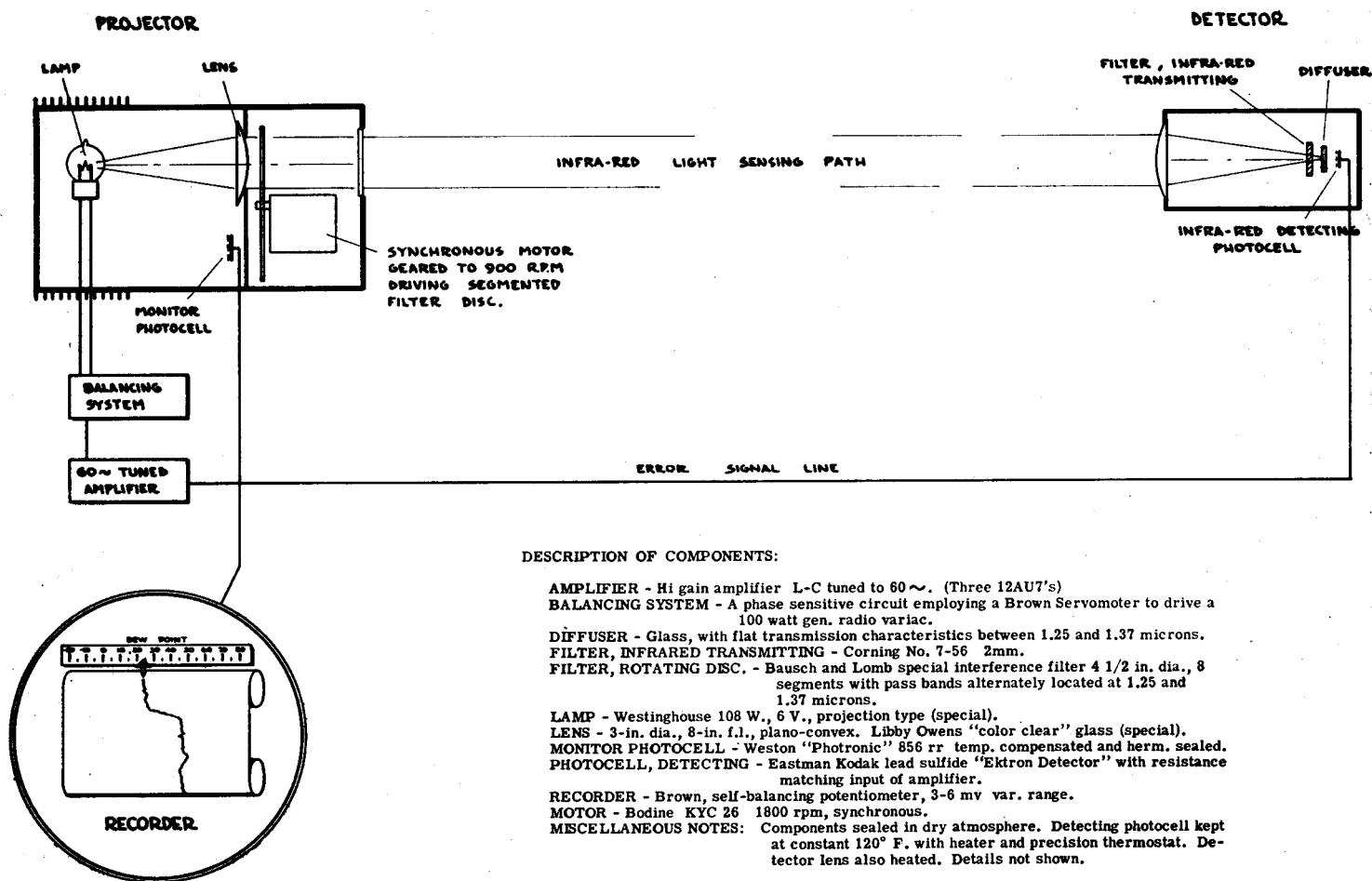


FIGURE 3.—Infrared hygrometer, schematic diagram of the single-beam system.

response and low noise level of the infrared photocell employed, extreme sensitivity to water vapor is attained without the necessity of high-gain amplification. The sensitivity of the instrument is limited by the harmonics induced by irregularity of the chopper and filters, and not by the noise level of the photocell or amplifier.

4. SINGLE BEAM

In working with the split-beam equipment it was found that a slight difference in the accumulation of dust on the optics in one light path over that in the other would result in large errors in water vapor measurements, effectively changing the calibration of the equipment. Likewise the passage of a rain drop or other foreign material such as a leaf through the sensing path would cause a spurious disturbance in the balance of the equipment. The obvious way to overcome this difficulty was to effect a design in which the reference band beam and the absorption band beam follow identically the same path from the lamp to the photocell. A single-path coincident beam arrangement is employed in the present hygrometer and is shown schematically in figure 3. It will be observed from figure 3 that the single-beam method differs from the split-beam arrangement only in the design of the optics. It will be observed also that the single-path design is achieved

through the use of a sector filter wheel. Instead of using two filters in a fixed position as in the split-beam arrangement, absorption and reference filter sectors are positioned alternately on a wheel which is rotated through the light path.

The filter wheel was fabricated for the Weather Bureau by Dr. A. F. Turner of the Bausch & Lomb Optical Co. It comprises eight 45° filter sectors; 4 absorption and 4 reference. The filters are deposited alternately on and sandwiched between two glass disks. The disks are approximately 4½ inches in diameter and ⅛ inch thick. The wheel is driven at 900 r. p. m. by a synchronous motor, at which speed the signal developed at the photocell due to an unbalance between reference and absorption band beam energies will appear at the amplifier as an alternating emf having a frequency of 60 cycles per second. This is the same signal frequency as that obtained in the split-beam instrument. Through the use of the filter-wheel single-beam arrangement, an accumulation of dust on any part of the optics (excepting the filter sectors) or the presence of foreign material in the sensing path affects both absorption and reference band beams alike with no change in calibration. A change of water vapor in the sensing path on the other hand will affect the amount of light passing through the absorption filter sectors and

make the wheel appear to the photocell to have four transparent and four opaque sectors. As a result a 60-cycle unbalance signal will develop which will be corrected by the self-balancing servo system.

LABORATORY TESTS

Optical bench tests made with the first filter wheels fabricated by Dr. Turner revealed the single-beam self-balancing system to be superior to any scheme that had been tried. Its stability was found to be far greater than that of other methods tested and its sensitivity was equalled only by the split-beam scheme. For the first time apparatus was available which would hold calibration for more than a day and the sensitivity exceeded expectations. For example, in the winter time when the absolute humidity was of the order of three to four grams of water per cubic meter, the equipment would detect almost immediately when a person entered or left the laboratory.

Many bench tests were made to determine (1) the feasibility of using the system in a hygrometer, and (2) the features that should be incorporated in a hygrometer design if such were effected. The objects of the most important of these tests and the results obtained are listed below:

a. Stability: No appreciable change in calibration was observed over test periods of several days. The subject is discussed further under "Further Studies".

b. Sensitivity: The sensitivity of the equipment is hard to define as it varies with the amount of water vapor in the sensing beam. It was found, however, that the sensitivity of the system at all moisture levels encountered is as great or greater than that of the recording potentiometer employed.

c. Speed of Response: An idea of the speed of response can be obtained from the following: With the servo system adjusted to "dead-beat" it was found that with a sudden change in absolute humidity of from approximately 7 grams per cubic meter to approximately 13 grams per cubic meter the recorder will come to within 90 percent of the final reading within 4 seconds. The recorder response alone is about 2.2 seconds for the same displacement. It is believed that the speed of response of the apparatus is determined mainly by the time constant of the lamp filament. A heavy lamp filament (20 amps, 6 volts) is employed to minimize the 120 cycle flicker resulting from the unit being powered from a 60-cycle supply.

d. Line Voltage Variation: Sudden line voltage changes were found to give small temporary variations in the record. Slow line voltage changes have no effect.

e. Effect of Lamp Aging: This test was performed by substituting lamps of varying ages and noting any resultant change in calibration.

It was observed that with increasing age, the calibration invariably shifted in the direction of a higher water vapor reading, with the greater shift occurring in the first few

hours of operation. The shift which occurred in the first 500 hours after a short seasoning period was quite small.

f. Effect of Temperature Change on Relative Response of Photocell: It was thought that temperature changes were affecting the relative response of the photocell to the reference and absorption wave lengths, and as a result the present instrument is equipped with a photocell oven to hold the cell at a constant temperature. Subsequent tests, however, indicate that the relative sensitivity of the photocell is probably more dependent upon the atmosphere around the cell than on the ambient temperature. The subject is discussed under "Further Studies."

g. Effect of Rain, Snow, and Fog: By locating the equipment in the window of the laboratory it was possible to expose part of the sensing path to rain, snow, and fog. Tests showed these hydrometeors to have little effect on the behavior of the equipment.

h. Effect of Smoke: Tests showed cigarette smoke to have no appreciable effect in medium concentrations. Concentrations approaching the point of completely attenuating the beam, however, shift the calibration to the "dry," indicating a differential scattering effect.

i. Effect of Moisture on Cover Glass and Lens: A visible sheet of water will shift the calibration of the apparatus to the "wet," whereas, moisture condensed in the form of small droplets will generally shift the calibration to the "dry." In the first instance the effect is apparently due to the differential transmission of water for the absorption and reference wave lengths. The second effect is apparently one of differential scattering. Surprisingly enough, large drops of water, if not covering too much of the lens, have little effect.

j. Effect of Obscuring Part of the Beam: If an opaque object is moved into the beam appreciably from either side a shift in calibration will result. The effect is apparently one of phase shift and is due to the fact that obscuring a reasonable portion of the beam is the same as shifting the position of the beam aperture at the filter wheel.

k. Effect of Pressure: As has been pointed out a pressure effect is to be expected. Simple tests made with a closed container in the sensing path indicate that the effect is small at pressures ordinarily existing at the earth's surface. The magnitude of the effect was not determined.

l. Effect of Temperature: No especial effort was made to determine if a temperature effect exists. It can be said, however, that over the temperature range encountered in the laboratory from summer to winter there was no evidence of measurable effect.

Many of the tests were conducted under conditions which were not ideal. Nevertheless for want of better information the design of the present instrument has been influenced to some degree by the results. It is contemplated repeating the work under conditions of more rigid control at an early date.

CALIBRATION

Inasmuch as the prime object of the work is to develop an instrument which can be used by the meteorologist, it was deemed advisable that a unit for use outdoors be

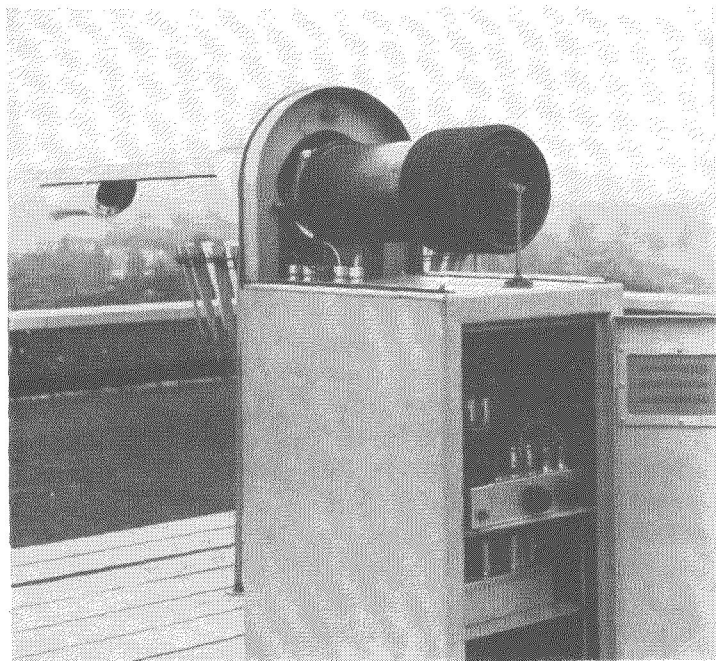


FIGURE 4.—Photograph of infrared hygrometer with hood removed and door open, showing moisture-tight transmitter compartment and method of housing electronic components.

designed and placed in operation as soon as a promising instrumental arrangement had been developed.

A photograph of the instrument as designed for making outdoors observations is shown in figure 4. The components of the projector and detector are completely enclosed in gas-tight compartments. These compartments are filled with dry nitrogen under pressure and desiccated by means of a drying agent. The detector and projector are rigidly fixed to an aluminum channel. This design, as well as fixing the length of the sensing path, exposes only two optical surfaces to the elements. It will be seen that the electronics and servo system of the unit are enclosed in a weatherproof housing which in turn provides a mounting for the optical system. The optical system is positioned so that the sensing path is exposed to free air at a height of approximately 4 feet.

The problem of calibration assumed its full significance with the advent of the outdoors installation. Considerable study had been given to the problem and it had been decided that a rigorous calibration could best be obtained through the use of a closed system and saturated atmospheres. While a reliable calibration was important to the installation, to obtain one by the selected method would require considerable time and some additional equipment. In the end it was decided to forego the absolute method in the interest of getting the equipment into operation at the earliest possible date. Consequently, the instrument was calibrated as it had been in preliminary laboratory tests by comparison with a psychrometer.

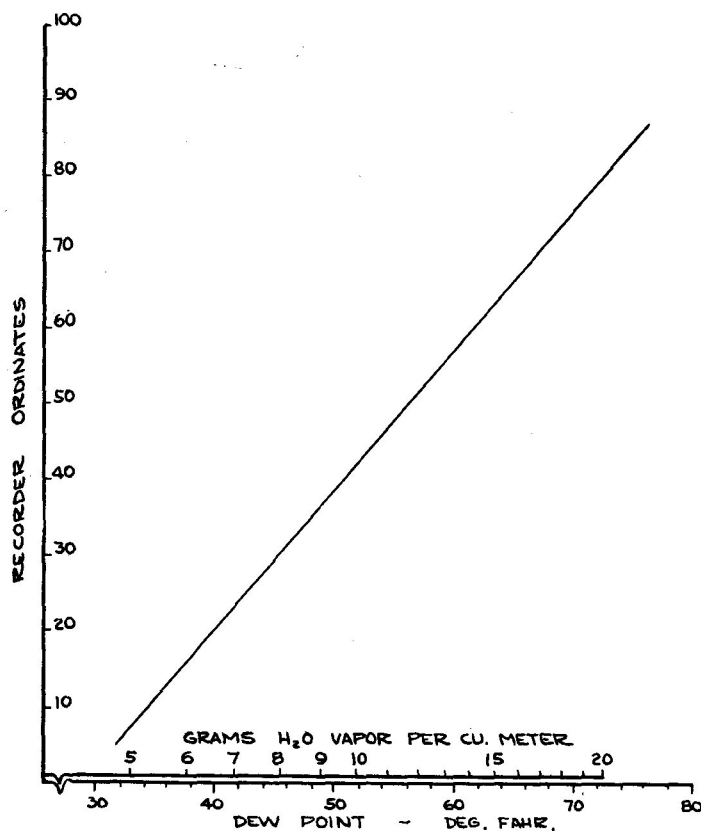


FIGURE 5.—Calibration curve for infrared hygrometer (tentative).

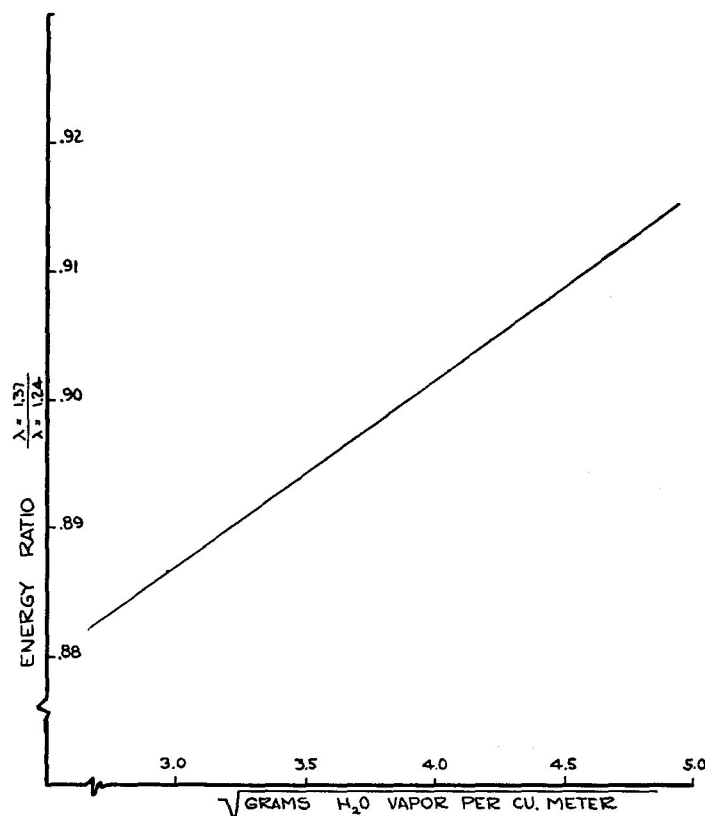


FIGURE 6.—Lamp energy ratio for $\lambda = 1.37\mu$ and 1.24μ vs. $(\text{absolute humidity})^{1/2}$

In this connection work had been carried out in the laboratory in an effort to calibrate by changing the length of the sensing path with a fixed ambient humidity. Through such a scheme it would be possible to calibrate from the ambient level down to zero distance. It was found that the scheme did not give reliable results with the equipment as designed. Tests indicated that the trouble is in the diffuser employed in front of the photocell and is one of differential scattering. The matter is being investigated further.

In calibrating the hygrometer there are three variables to be considered. These are the quantity of water vapor in the sensing path, the ambient pressure, and the ambient temperature.

As pointed out, the pressure and temperature functions are quite complicated. Enough is known of these functions, however, to indicate that for the average weather station the overall temperature and pressure effects will be small; perhaps of the order of the experimental error of the equipment. For this reason no attempt was made to eliminate temperature and pressure effects. A more rigorous calibration involving these factors will be made and reported upon later.

Inasmuch as water vapor absorption is a function of the concentration of water molecules in the sensing path, it is obvious that the hygrometer may be calibrated in terms of absolute humidity, i. e., the number of grams of water per cubic meter. Absolute humidity, however, is a term not ordinarily employed in routine synoptic meteorology. The hygrometric unit usually sent over the teletypewriter and placed on weather maps is the dew point. Unfortunately, the relation between absolute humidity and dew point involves absolute temperature. It can be shown, however, that if the hygrometer is calibrated in terms of dew point at some intermediate temperature the instrument will operate over the usual range of station temperatures throughout the year without being in error at any time by more than a percent or two in terms of absolute humidity. If higher accuracy is required a correction can, of course, be calculated and applied. Because of its obvious utility and because the meteorologist is accustomed to thinking in terms of dew point, the hygrometer has been calibrated in terms of dew point as well as absolute humidity.

Figure 5 shows a tentative calibration of the instrument in terms of recorder response versus dew point and absolute humidity. This calibration was obtained by plotting the dew point and absolute humidity of the ambient atmosphere as determined by a sling psychrometer against recorder response. Observations were made at approximately 80° F. in a closed room where there was limited control of the absolute humidity.

Figure 6 shows energy ratio $\left(\frac{\lambda=1.37\mu}{\lambda=1.24\mu}\right)$ of lamp output versus the square root of the absolute humidity. It will be seen from the figure that over the range of humidities

covered by the calibration, the instrument is operating in the square root region of the water vapor absorption function. Consequently, the rate of change of energy ratio with respect to change in absolute humidity will increase with a decrease in absolute humidity resulting in an increase in sensitivity with a decrease in humidity.

Figure 7 is a photograph of the outdoors installation on the roof of the Weather Bureau Administration Building. The wiring required for the installation is a 115-volt, 60-cycle power line and one telephone pair for connecting the output of the monitor photocell to the recorder. The recorder is installed in an instrument panel cabinet in the observatory, a distance of about 75 feet from the hygrometer. The equipment was placed in operation May 1, 1953, and has since provided continuous humidity records.

Figure 8 shows an interesting example of the type of record obtained. Because of the fast time response of the equipment, humidity changes and excursions are coming to light, which are exciting the interest of meteorologists. The figure shows the record for a meteorological situation that occurred over Washington on July 22, 1953. At 1330 EST the dry-bulb temperature at Washington National Airport, about five miles southeast of the exposure site of the hygrometer, was 87° F. and the dew

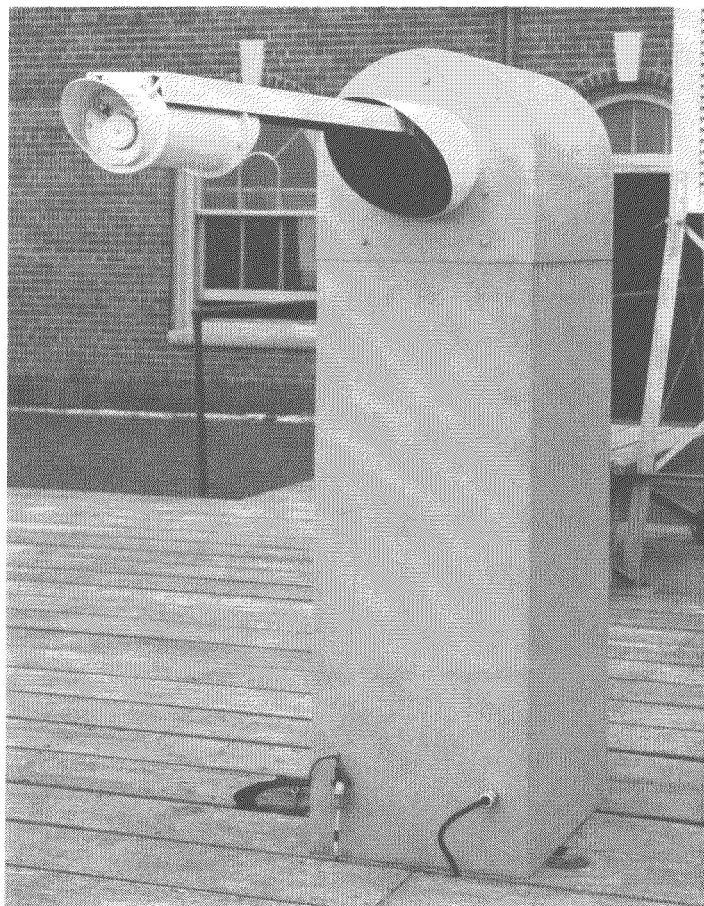


FIGURE 7.—Photograph of optical hygrometer installation on roof of U. S. Weather Bureau Administration Building, Washington, D. C.

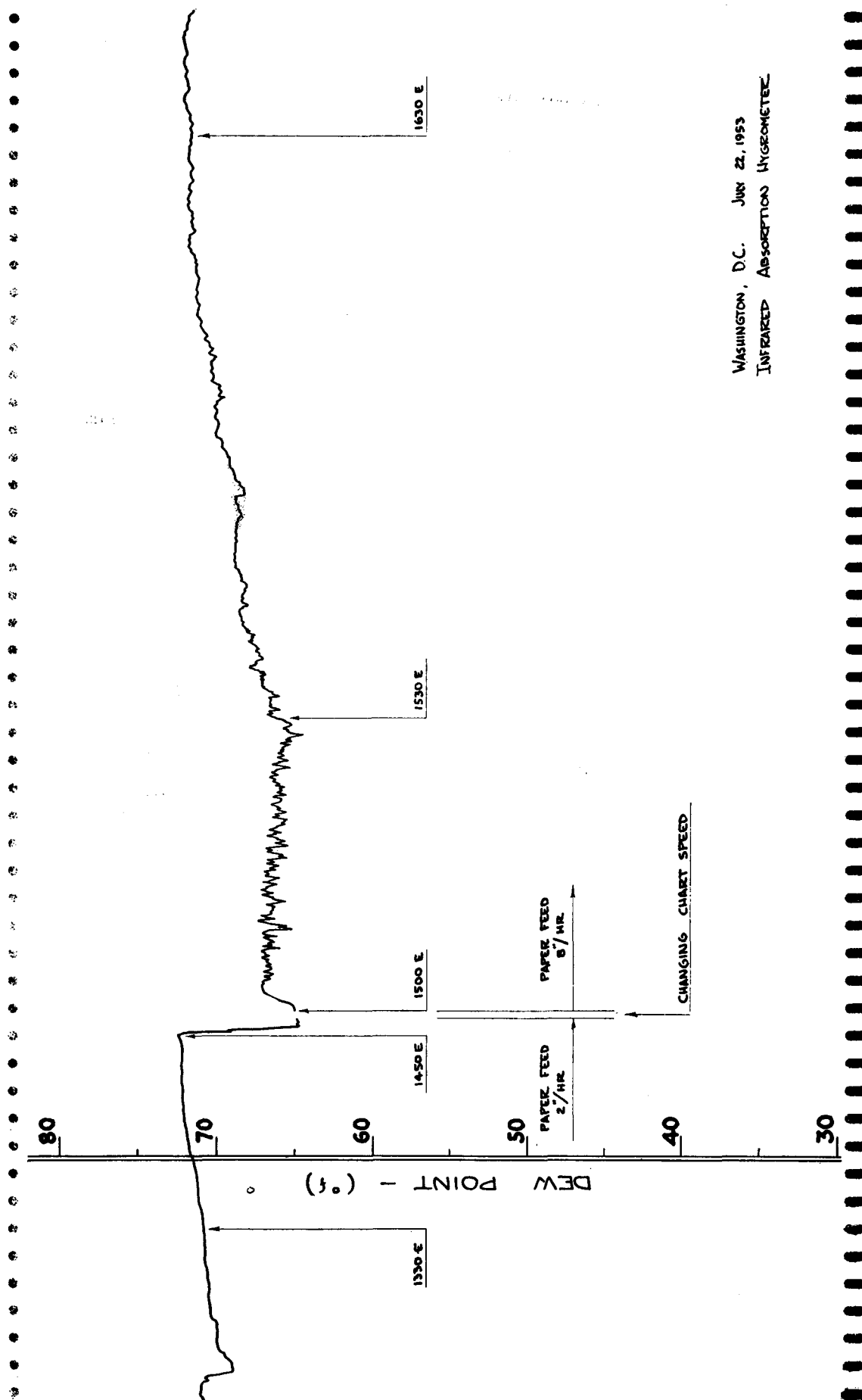


FIGURE 8.—A portion of a typical infrared hygrometer record. Chart shows a rapid change in atmospheric moisture in connection with thunderstorm conditions over Washington, D. C., July 22, 1953.

point was reported as 71° F. The hygrometer record taken on the Weather Bureau Administration building showed a similar dew point of 71° at the same time. During the ensuing hour the temperature at the airport increased by about 3° while the dew point dropped 1°. During the same period the hygrometer showed an increase in dew point of 1° reaching a maximum just over 72° F. at 1450 EST. At this time a very light rain began at the Weather Bureau Office in Washington and the dew point dropped from 72° F. to 65° F. in approximately 3 minutes. An alert observer, sensing an unusual situation, changed the recorder chart speed to 8 inches per hour, 4 times its previous value. This change was completed approximately at 1500 EST at which time heavy rain began to fall, and in a few moments the dew point recovered to an average value of about 66° F. Heavy rain continued to fall until about 1530 EST during which time the dew point appeared to fluctuate one to two degrees Fahrenheit about a mean value of 66° F. At 1530 EST the dry bulb was 76° F. and the dew point was 69° F. at the Washington National Airport. At the end of the heavy rain the dew point increased slowly and the amplitude of the fluctuations decreased. About an hour was required following the heavy rain for the dew point to return to its initial value. At 1630 EST Washington National Airport showed a dry bulb temperature of 82° F. and a dew point of 72° F., at the same time the hygrometer registered a dew point of 72° F.

The synoptic situation at 1330 EST responsible for the above weather was as follows: Washington was in the warm sector of a cyclone centered several hundred miles to the north of the Great Lakes. A warm front was oriented in an east-west direction along the Maryland-Pennsylvania line about 70 miles west of Washington. A cold front extended southward from Toledo, Ohio, to the vicinity of Little Rock, Ark., and a squall line preceded the front by about 120 miles from the vicinity of Erie, Pa., to Nashville, Tenn. Thunderstorms were recorded in the vicinity of Quantico, Va., about 30 miles south-southwest of Washington and scattered swelling cumulus clouds were observed at Washington below a layer of thin high cirrus clouds.

FURTHER STUDIES

Operation of the instrument for the past several months has brought to light information which will be important in the design of future equipment. For the most part, it is believed that the performance has been good in view of the fact that the equipment is new. The amplifier and balancing system have operated without a single failure in electronic components. One detector photocell and one monitor photocell have been replaced but the necessity for this is believed to have arisen from a lightning discharge in the immediate vicinity. The filter wheel has been replaced twice because of a slow drift in the calibration. This effect is believed to be due to the fact that the wheel was not assembled and sealed properly. As originally installed, the detector

and projector compartments contained phosphorus pentoxide drying agent. Sublimation of this agent gave difficulty in that it clouded the optics. The compartments now employ silica gel.

To improve and refine the design further studies are now in process. In particular, studies are being made to:

1. Simplify the design of the optics and electronics.
2. Devise a simple and reliable scheme for range changing.
3. Develop a fast and reliable method for effecting a calibration.
4. Determine a suitable material for use as a photocell diffuser.
5. Determine the effect of temperature and pressure.
6. Ascertain if the detector photocell heater is required.
7. Develop a means for checking the "figure of merit" of a filter wheel.
8. Determine the optimum sensing path length.
9. Reduce the overall size and weight of present equipment.

Some work has been carried out on many of these problems, but more remains to be done.

REFERENCES

1. A. Wexler and W. G. Brombacher, "Methods of Measuring Humidity and Testing Hygrometers," National Bureau of Standards, *Circular 512*, Sept. 28, 1951.
2. L. W. Foskett and N. B. Foster, "A Spectroscopic Hygrometer," *Bulletin of the American Meteorological Society*, vol. 24, No. 4, Apr. 1943, pp. 146-153.
3. A. F. Turner, "Some Current Developments in Multi-Layer Optical Films," *Le Journal de Physique et le Radium*, Tome 11, Juillet 1950, pp. 444-460.
4. A. F. Turner, Bausch & Lomb Optical Company, Rochester, New York, by conversations with the authors.
5. S. Pakswar, "Lead Sulphide Photoconductive Cells," *Electronics*, vol. 22, May 1949, pp. 111-115.
6. E. K. Plyler and W. W. Sleator, "Further Study of the Absorption of Infrared Radiation by Water Vapor," *Physical Review*, 2d Series, vol. 37, No. 11, June 1, 1931, pp. 1493-1507.
7. F. E. Fowle, "The Spectroscopic Determination of Aqueous Vapor," *Astrophysical Journal*, vol. 35, No. 3, April 1912, pp. 149-162.
8. W. W. Sleator and E. R. Phelps, "The Fine Structure of the Near Infrared Absorption Bands of Water-Vapor," *Astrophysical Journal*, vol. 62, No. 1, July 1925, pp. 28-48.
9. W. M. Elsasser, "New Values for Infrared Absorption Coefficient of Atmospheric Water Vapor," *Monthly Weather Review*, vol. 66, No. 6, June 1938, pp. 175-178.
10. N. B. Foster, "A Recording Daylight Illuminometer," *Illuminating Engineering*, vol. XLVI, No. 2, Feb. 1951, pp. 59-62.